Deep Drilling into a Hawaiian Volcano

Scientists recently drilled through a Hawaiian volcano to a depth of 3,098 meters below sea level.

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Hawaiian volcanoes are the most comprehensively studied on Earth due, in part, to their active volcanism, their accessibility and location within the United States, and their excellent exposure. Nevertheless, most of the eruptive history of each of the five volcanoes exposed on the island of Hawaii is inaccessible because it is buried by younger lava flows or exposed only below sea level. For those parts of Hawaiian volcanoes above sea level, erosion typically exposes only a few hundred meters of buried lavas (out of a total thickness of up to 10 kilometers or more). Available samples of submarine lavas extend the time intervals of individual volcanoes that can be studied. However, the histories of individual Hawaiian volcanoes during most of their 1-million-year passages across the zone of melt production are largely unknown.

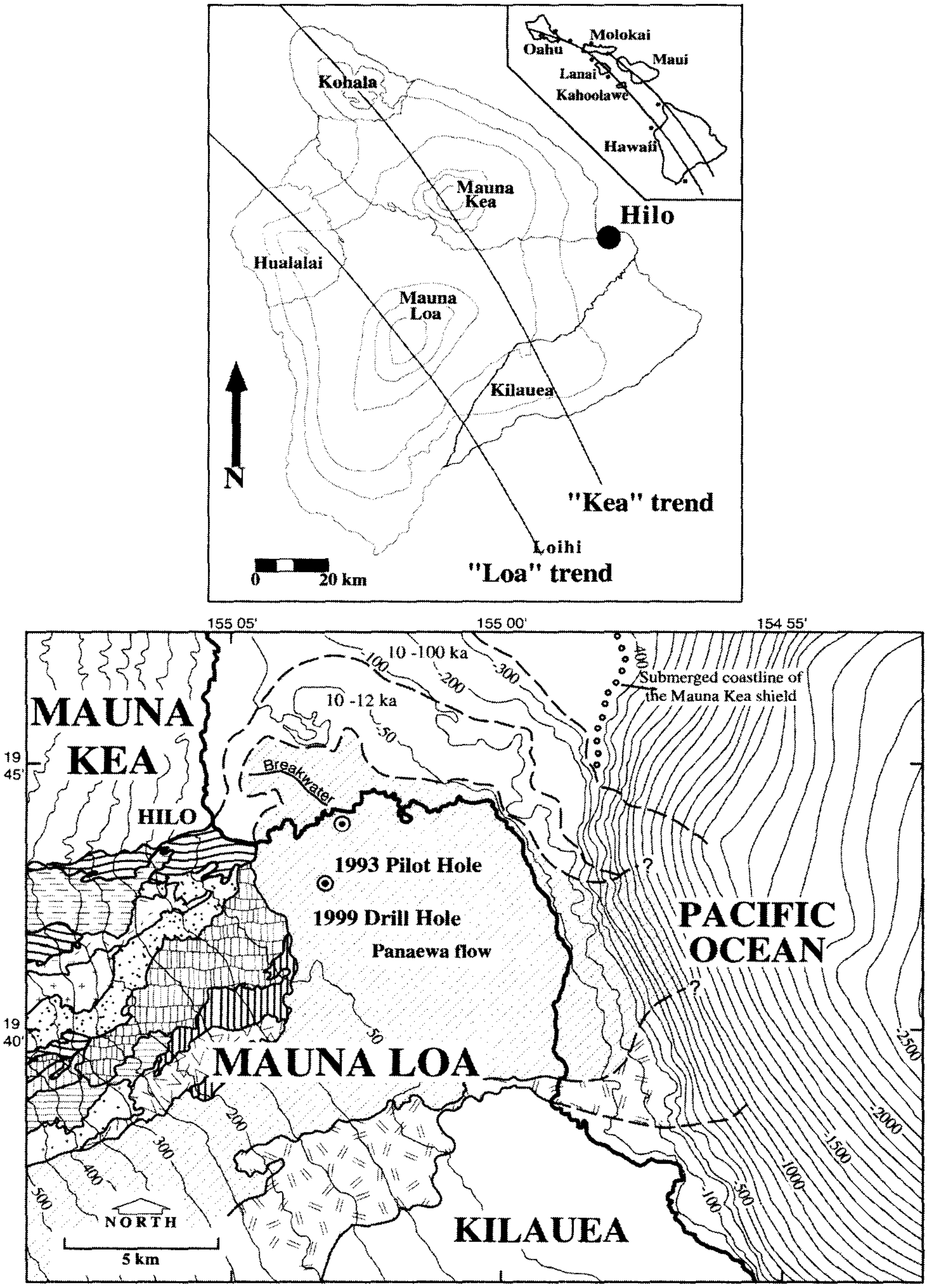
If stratigraphic sequences of lava flows from Hawaiian or other oceanic volcanoes spanning long time periods could be obtained, they would provide valuable probes of plume structure and magmatic processes. Continuous core drilling through lava sequences on the flanks of oceanic volcanoes is the only way to sample lava flows that span the entire eruptive history of a volcano. Imagine the idealized growth of a volcano as one lava flow, then another on top of it, and so on; obviously, the older flows are buried by the younger ones and hidden from view, but if we could start at the top and drill all the way to the bottom, we would sample all the lava flows in reverse order. Although real volcanoes are more complex than a simple layer cake, this helps to illustrate the concept behind the drilling project.

The opportunity to probe the long-term history of a Hawaiian volcano by drilling has led an international group of scientists to core-drill into Mauna Kea volcano on the island of Hawaii. Planning for the Hawaii Scientific Drilling Project (HSDP) began in 1986. The objective of the HSDP is to recover and characterize as nearly a continuous sequence of core samples as possible to a depth of at least 4.5 kilometers.

In the fall of 1993, the National Science Foundation (NSF) supported the core-drilling of a 1.06-kilometer-deep "pilot hole" through a veneer of Mauna Loa flows into the flank of Mauna Kea volcano in Hilo, Hawaii (see map on page 12). About 90% of the core was recovered, yielding a long record of fresh subaerial lavas extending back 400 thousand years. Petrological, geochemical, geomagnetic, and volcanological characterization of the recovered core, downhole logging, and fluid sampling provided a view of the evolution and internal structure of a major oceanic volcano that was unavailable from surface exposures. Detailed information on the pilot hole can be found at the HSDP Web site (http://expet.gps.caltech.edu/Hawaii_project.html) and in the May 1996 special issue of AGU's *JGR*. Based on the success of the pilot drill hole, the first of two phases of deep drilling began in Hilo on March 15, 1999, at a site 2 kilometers south of the pilot hole. Supported primarily by the NSF, but with significant support from the International Continental Drilling Program in Potsdam, Germany, this first phase of deep drilling was completed on September 23, 1999, at a depth of 3,098 meters below sea level (mbsl).

Site Selection, Drilling, Downhole Logging

An abandoned quarry on the grounds of the Hilo International Airport was chosen as the site for the drill hole (see map on page 12). As was the case for the pilot hole, the site was chosen to be far from volcanic rift zones, so as to minimize chances of encountering intrusives, alteration, and high-temperature fluids; to be close to the coastline, so as to minimize the thickness of subaerial lavas that would need to be penetrated to reach the older, submarine parts of the Mauna Kea section; and in an industrial area, to minimize environmental and community impacts.



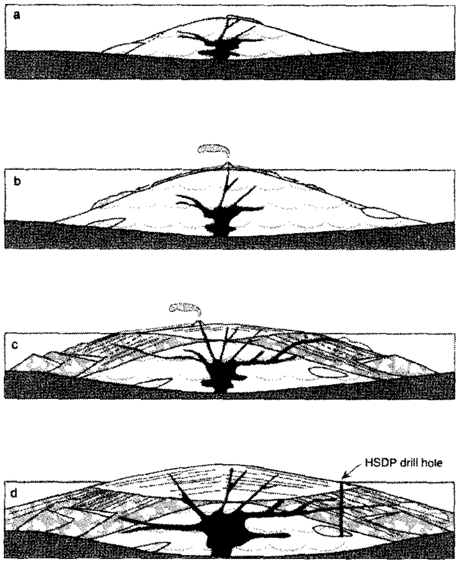
Location map for the Hawaii Scientific Drilling Project pilot hole (drilled in 1993) and the first phase of deeper drilling (1999).

Although the Mauna Kea section was the primary target, this choice of site required drilling through a veneer of Mauna Loa flows, thereby providing additional information on the Mauna Loa volcanic succession as a complement to the coverage of the Mauna Kea sequence.

Drilling into the volcano is not as difficult—or as dangerous—as it might sound. For one thing, the volcano is no longer active, so there is very little chance of encountering hot magma. Also, the choice of the drilling site purposely avoided any areas where water has been heated up by nearby magma bodies. The most difficult parts of this drilling project turned out to be coring through highly fractured rocks and controlling water flows out of the drill hole from high-pressure underground aquifers.

Stratigraphy Interpretation in Terms of Evolution

An integrated program of determinations of ages, chemical and isotopic compositions, magnetic and



Series of illustrations demonstrating the progressive evolution of a Hawaiian volcano and showing the expected sequence of deposits with depth in the hole: (a) submarine/seamount phase (e.g., Loihi) showing the possibility of submarine landslides; (b) an emergent volcano, showing the eruption of subaerial lavas and the formation of hyaloclastites by slumping of near-shore volcaniclastic sediments; (c) main stage of shield building (e.g., Kilauea), illustrating major landslides, the formation of "massive" submarine units as tube-fed flows extending from subaerial to submarine conditions, the eruption of pillow lavas through the submarine flanks of the volcano, and shallow intrusives into the volcano flanks, including feeders for submarine flank eruptions; (d) after the end of shield-building (e.g., Mauna Kea), showing the near-shore location of the HSDP drill hole.

physical properties, and petrography of the recovered samples is underway and will continue over the next year. Our expectation is that the data will contribute to understanding mantle plumes, the internal structure and evolution of a major oceanic volcano, and related magmatic and volcanic processes. However, even in advance of the detailed characterization of the core that these studies will provide, the onsite characterization of the stratigraphic column and the preliminary geochemical data that are available provide insights into the internal structure and evolution of a Hawaiian volcano.

The idealized stratigraphic sequence expected at a near-shore site such as Hilo, which is located 17 kilometers south of the east rift of Mauna Kea, can be understood with the progression in the growth of a Hawaiian volcano as illustrated in the figure above. Although the overall stratigraphic section encountered during drilling is similar to that anticipated from the simple sequence shown in the figure above, it differs from it in several respects:

• The transition from pillow lavas to debris flows might be expected based on the figure above to be abrupt, reflecting the unidirectional outward growth of the volcano, yet the actual section has these two rock types interfingered over a depth interval of at least 1 kilometer. Although it is not surprising that the transition from pillows to debris is not in fact sharp, the broad transition observed was not anticipated.

• Pillow lavas were encountered in the section at a depth much shallower than expected. Based on the simple model illustrated in the figure, pillow lavas would not be expected shallower than 4-5.5 kilometers below sea level in the core; yet they first appear at a depth of 2 kilometers below sea level.

There are several possible explanations for the shallow occurrence of pillow lavas in the core, including the following. First, at the phase of its growth that controlled the stratigraphy of the drill site, the east rift of Mauna Kea could have had a shallow slope of 3-4°. Although this is not the norm, some Hawaiian rifts have slopes that are this shallow, so this cannot be ruled out. Second, the east rift of Mauna Kea may not always have been in its current location. For example, if it was initially further south, closer to the drilling site in Hilo, this could explain the shallower occurrence of pillows, and a complex interfingering of pillows and debris might accompany an evolving position of the rift relative to the drill site during movement of the rift toward its current location. Third, eruption of magma through the debris draping the submarine flanks of Mauna Kea's east rift could have produced abundant, undegassed pillow lava much higher up in the section than would be predicted from the simple model of Hawaiian volcano growth illustrated in the figure. Support for this explanation comes from studies showing that submarine Hawaiian eruptions are not confined to rift zones.

• The "massive" basalts that make up 10% of the upper kilometers of the submarine section are not well understood. We have tentatively identified them as subaerial flows that continued past the shoreline and flowed substantial distances in lava tubes (~4 km given their depths and assuming a submarine slope of 10°). Such flows do occur in younger Hawaiian submarine sections and are shown as an illustration in panel c. However, the absence of pillow structures associated with these units and the rarity of such flows on modern-day Hawaii are problematic.

• The presence of intrusives at relatively shallow depths in the core was not expected, given the distance from the summit and the east rift of Mauna Kea. These units could be feeders for off-rift eruptions, or they could be evidence that Mauna Kea's east rift was previously further south than its current location.

How Deep Can We Drill?

The current schedule calls for remobilization of drilling equipment to the site during the last quarter of 2001 to re-enter the hole and continue the drilling program.

The 1999 phase of the deep drilling effort was able to reach a depth that was nearly 650 meters deeper than originally envisioned for this phase. As a result, we will be able to start the next phase of drilling by opening the hole to a diameter of 15.9 centimeters to the current depth of 3.1 kilometers below sea level, and casing will be installed from the surface to that depth. From that depth, we will then core to a maximum depth determined by hole conditions and available funds. Based on the coring conditions encountered near the close of the 1999 phase of drilling, we have a target depth of 4.5 kilometers below sea level. However, the coring system is capable of a maximum depth of slightly more than 6.5 kilometers. If drilling conditions and funding allow, this would enable us to approach and perhaps even penetrate the Cretaceous ocean floor beneath Mauna Kea.

Source: *Eos*, March 27, 2001, p. 149.

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A Few Words from the Authors

Don DePaolo was born and raised in western New York state. He received a B.S. from the State University of New York at Binghamton in 1973 and a Ph.D. from the California Institute of Technology in 1978. He was a professor at UCLA from 1978–1988 and has been on the faculty at U.C. Berkeley since 1988, where he teaches petrology and geochemistry. He is also a Senior Faculty Scientist at the E.O. Lawrence Berkeley National Laboratory. His research involves using mass spectrometry to study the geochemistry of rocks and minerals, addressing such questions as the age and origin of igneous and metamorphic rocks, the evolution of the Earth's mantle, and the geochemistry of Earth's oceans in the geologic past. He is currently on leave from Berkeley and doing research at the Australian National University as a John Simon Guggenheim fellow.

Ed Stolper was born and raised in the Boston area. He received an A.B. from Harvard College in 1974, an M.Phil. from the University of Edinburgh, Scotland, in 1976, and his Ph.D. from Harvard University in 1979. He joined the faculty at the California Institute of Technology in 1979 and has been there ever since. His research involves using experiments at high pressure and temperature, theory, and observation to understand the origin and evolution of igneous rocks on the Earth and other planets (including the Moon, Mars, and asteroids). He is currently chairman of the Division of Geological and Planetary Sciences at Caltech.

Don Thomas got his B.S. in physics and chemistry from Dickinson College in Pennsylvania, an M.S. from Oregon Graduate Center, where he studied the surface chemistry of platinum, and a Ph.D. in chemistry from the University of Hawaii, where he began his fascination with volcanoes in a study of the chemical and isotopic compositions of the volcanic gases of Kilauea. Don is currently doing research to answer questions about how water moves through large oceanic volcanic structures and how it reacts with the volcanic rocks. He also works to understand mechanisms of volcanic eruptions, with the ultimate goal of predicting when eruptions might occur, and teaches classes for international students on techniques for monitoring active volcanoes. He is active in helping Hawaiian residents appreciate the wonders of the unique natural environment in which they live, while at the same time alerting them to the risks of living near active volcanoes.